Water Quality Protection: Symposium. College Park, MD: University of Maryland. www.sawgal.umd.edu/DrainageDitches/2006_tourandsymposium/.

Skaggs, R.W., M.A. Breve, and J.W. Gilliam. 1994. Hydrologic and water-quality impacts of agricultural drainage. Critical Reviews in Environmental Science and Technology 24:1-32.

Skaggs, R.W., and J.V. Schilfgaarde, eds. 1999. Agricultural drainage. Agronomy Monograph 38. Madison, WI: American Society of Agronomy-Crop Science Society of America-Soil Science Society of America.

Skaggs, R.W., G.M. Chesheir, and B.D. Phillips. 2005a. Methods to determine lateral effect of a drainage ditch on wetland hydrology. Transactions of the ASAE 48:577-584.

Skaggs, R.W., A.A. Youssef, G.M. Chescheir, and J.W. Gilliam. 2005b. Effect of drainage intensity on nitrogen losses from drained lands. Transactions of the ASAE 48:2169-2177.

Smith, D.R., and E.A. Pappas. 2007 Effect of ditch dredging on the fate of nutrients in deep drainage ditches of the Midwestern United States. Journal of Soil and Water Conservation 62(4):252-261.

Smith, D.R., E.A. Warnemuende, B.E. Haggard, and C. Huang. 2006. Dredging of drainage ditches increases short-term transport of soluble phosphorus. Journal of Environmental Quality 35:611-616.

Stott, R., and C.C. Tanner. 2005. Influence of biofilm on removal of surrogate faecal microbes in a constructed wetland and maturation pond. Water Science and Technology 51:315-322.

Strock, J.S., C.J. Dell, and J.P. Schmidt. 2007. Managing natural processes in drainage ditches for nonpoint source nitrogen control. Journal of Soil and Water Conservation 62(4):188-196.

Vadas, P.A., M.S. Srinivasan, P.J.A. Kleinman, J.P. Schmidt, and A.L. Allen. 2007. Hydrology and groundwater nutrient concentrations in a ditch-drained agroecosystem. Journal of Soil and Water Conservation 62(4):178-188.

van Schilfgaarde, J. 1971. Drainage yesterday, today, and tomorrow. *In* Proceedings of the ASAE National Drainage Symposium. St. Joseph, MI: American Society of Agricultural Engineers.

van Strien, A.J., J. Van Der Linden, T.C.P. Melman, and M.A.W. Noordervliet. 1989. Factors affecting the vegetation of ditch banks in peat areas in the western Netherlands. Journal of Applied Ecology 26:989-1004.

van Strien, A.J., T. Van Der Burg, W.J. Rip, and R.C.W. Strucker. 1991. Effects of mechanical ditch management on the vegetation of ditch banks in Dutch peat areas. Journal of Applied Ecology 28:501-513.

Vaughan, R.E., B.A. Needelman, P.J.A. Kleinman, and A.L. Allen. 2007. Spatial variation of soil phosphorus within a drainage ditch network. Journal of Environmental Quality 36:1096-1104.

Vaughan, R.E., B.A. Needelman, P.J.A. Kleinman, and M.C. Rabenhorst. Forthcoming. Morphology and characterization of ditch soils at an Atlantic Coastal Plain farm. Soil Science Society of America Journal.

Hydrology and groundwater nutrient concentrations in a ditch-drained agroecosystem

P.A. Vadas, M.S. Srinivasan, P.J.A. Kleinman, J.P. Schmidt, and A.L. Allen

Abstract: Groundwater nitrogen (N) and phosphorus (P) transport from ditch-drained, cultivated fields has not been adequately investigated in the Chesapeake Bay watershed. We monitored hydrology and groundwater N and P concentrations in 26 shallow (~3 m [10 ft]) wells for 27 months on a heavily ditched, poultry-grain farm on Maryland's Lower Eastern Shore. Water tables fluctuated above and below shallow ditches, but were always higher than deep ditches. Thus, groundwater flow to shallow ditches was intermittent, but flow to deep ditches was continuous. Water tables rose rapidly with rain, but drained back from 15 to 60 cm (6 to 24 in) the first day after rain. The rate of water table fall decreased rapidly thereafter. Water tables frequently perched on top of subsoil clay horizons. Although perching persisted only 24 to 48 hours, nutrient transport could be accelerated if rapid, lateral movement of water to ditches occurs. Frequent and widespread concentrations of groundwater NO_3-N greater than 10 mg L^{-1} show subsurface N loss from the farm is probable. High concentrations of dissolved P existed in groundwater, but P movement in groundwater was restricted. Rain infiltrating through topsoils mobilized soil P into groundwater and moved considerably high concentrations of P as deep as 1.5 m (4 ft), where elevated P concentrations persisted for days or weeks. Groundwater P concentrations were greatest where high water table hydrology combined with the greatest soil P concentrations. Delivery of groundwater P to shallow ditches was apparently controlled by near-ditch soil P conditions, while P delivery to deep ditches was controlled by how deep groundwater flowed. Therefore, limiting soil P accumulation in near-ditch zones may help reduce P delivery to shallow ditches, and increasing the length of groundwater flow paths through low-P subsoils may help reduce P delivery to deep ditches.

Key words: ditch-drained agroecosystem—groundwater—hydrology—nitrogen concentration—phosphorus concentrations—water tables

Nitrogen (N) and phosphorus (P) are the primary nutrients that accelerate eutrophication in fresh surface waters (Carpenter et al. 1998). Eutrophication is an aging process where influxes of nutrients promote excessive plant and algae growth and can limit water use for recreation, industry, and drinking. On the Delmarva Peninsula in the Mid-Atlantic region of the United States (figure 1), the Chesapeake Bay and Delaware and Maryland's Coastal Bays are subject to eutrophication-related algal blooms (Boesch et al. 2001; Boynton 2000).

The Delmarva Peninsula is home to one of the most concentrated poultry industries in the United States, and annually produces nearly 600 million birds at a wholesale value of nearly $2 billion. Nearly all of the 750,000 tons of poultry manure annually produced

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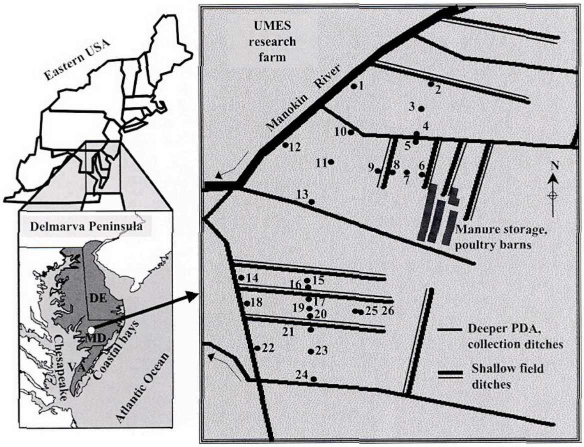
Figure 1
Location of the University of Maryland Eastern Shore research farm on the Delmarva Peninsula and the location of the 26 groundwater wells relative to ditches and the Manokin River on the farm.



by this industry is land-applied locally to agricultural fields as a source of nutrients for crops, often at agronomically excessive rates. Manure application has been implicated in the contamination of groundwater and surface water as N and P are transferred from soils to the surrounding environment (Boesch et al. 2001; Butler and Coale 2005; Mozaffari and Sims 1994; Sims and Wolf 1993). Delaware, Maryland, and Virginia have thus implemented policies to reduce agricultural N and P transport to surface and groundwaters (Sims and Gartley 1996; Coale et al. 2002; Weld et al. 2000).

On the Delmarva Peninsula, poultry manure is routinely applied to cultivated fields drained by ditches. Organized land drainage on the Delmarva Peninsula began in the late 1700s, became a large-scale endeavor by the early 20th century, and has left an extensive network of drainage ditches throughout portions of the Delmarva Peninsula. Ditches improve crop production in poorly drained soils by rapidly removing surface water from fields and lowering water tables. Consequently, ditches can accelerate groundwater nutrient transport from fields to surface waters (Mozaffari and Sims 1994; Sallade and Sims 1997a, 1997b).

Soils do not have a great capacity to retain NO_3-N, which is the dominant chemical form of N in aerobic soils; N added to soils in fertilizers or manures often leaches downward in soils and moves with groundwater (Staver and Brinsfield 1998). This is not always the case for P. Soils typically have a strong affinity to bind P, and most P added to soils in fertilizers or manures remains in the topsoil (Malhi et al. 2003; Rechcigal et al. 1985). Downward leaching of P and transport in groundwater has thus been considered unimportant and is not well understood. However, P leaching and transport in groundwater has been observed in sandy soils with limited capacity to retain P, in soils where accumulation of P in topsoils from fertilization has saturated soil retention capacity, and in artificially drained soils with preferential flow pathways and relatively short groundwater flow distances (Sims et al. 1998).

In the United States, considerable research has investigated the role of agricultural drainage on nutrient transport; however, it has been conducted primarily in North Carolina, South Carolina, Florida, and Georgia, and more for N than P (Thomas et al. 1995). Research in the Mid-Atlantic region is limited and in many instances nonexistent (Shirmohammadi et al. 1995). Despite the widespread study of agricultural nutrient transport and the integral nature of drainage ditches, groundwater nutrient transport in ditch-drained soils is not well understood, especially for P (Sims et al. 1998).

Given the accumulation of N and P in soils and the hydrologic activity of ditch-drained agroecosystems on the Delmarva Peninsula, we hypothesized that N and P transport in groundwater may be greater than is currently realized. The long-term objective in the ongoing field study described in this paper is to quantify N and P transport in groundwater from a heavily ditch-drained farm on Maryland's Lower Eastern Shore. In this paper, we report the findings of the first two years of field monitoring and describe the hydrology and groundwater N and P status. We also describe how variations in soil chemical and physical properties and drainage hydrology may apparently control the fate of groundwater N and P.

Materials and Methods

Site Description. We conducted research at the University of Maryland Eastern Shore (UMES) research farm (38°12'22" N, 75°40'35" W) in Princess Anne, Maryland (figure 1). The farm relief is flat, with an approximate elevation of 5.5 m (18 ft) above sea level. Annual rain averages 111 cm (44 in). Farm soils belong to the poorly-drained Othello series (fine-silty, mixed, active, mesic Typic Endoaquult) and typically have 50 to 75 cm (20 to 30 in) thick, silt loam topsoils that are underlain by 20 cm (8 in) thick, silty clay subsoils, which are in turn underlain by very coarse marine sediments. Silty clay subsoils and their abrupt texture change with the deeper coarse marine sediments impede drainage. Therefore, all fields are drained by shallow field (~0.3 to 1.0 m [1 to 3 ft] deep) and deeper Public Drainage Association (PDA) ditches (~1 to 3 m [3 to 9 ft] deep) (figure 1). Shallow ditches drain individual fields in a parallel pattern and flow into deeper collection or PDA ditches running perpendicular to shallow ditches. Collection ditches drain into PDA ditches, which in turn drain into the Manokin River, a tributary of the Chesapeake Bay.

The farm was a poultry operation until 1997, with a more than 20-year history of manure application to soils. Farm soils have P concentrations greatly in excess of crop requirements (Mehlich-3 P > 60 mg kg^{-1} [0.00096 oz lb^{-1}]), with Mehlich-3 P concentrations as great as 450 mg kg^{-1} (0.0072 oz lb^{-1}) in surface horizons and 80 mg kg^{-1} (0.0013 oz lb^{-1}) in subsurface horizons as deep as 1 m (3 ft). Chickens are still raised on the farm, but less frequently and in lesser quantities than before 1997. Fields are cropped to corn, wheat, and soybean and are fertilized to meet corn N demand (~150 bushel ac^{-1} yield goal) using manure from the farm (50 to 150 kg N ha^{-1} [133 lb ac^{-1}] and 40 to 120 kg P ha^{-1} [36 to 107 lb ac^{-1}]) or liquid ammonia (120 to 150 kg N ha^{-1} [107 to 133 lb ac^{-1}]). These nutrient and hydrology conditions are representative of many farms in the region.

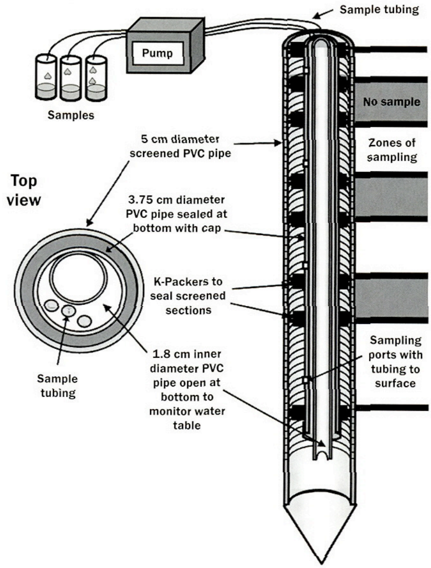
An ongoing, intensive research project at the University of Maryland Eastern Shore research farm is being conducted by the University of Maryland at Eastern Shore and College Park, and the USDA Agricultural Research Service in University Park, Pennsylvania. A wide array of runoff, drainage, ditch, and climate monitoring equipment has been installed to investigate the effect of field, manure, and ditch management on N and P export (see also Kleinman et al. 2007 and Schmidt et al. 2007).

Groundwater Well Design and Installation. In the fall 2003, we installed 26 groundwater wells at both field centers and ditch edges in northern and southern portions of the farm (figure 1). We positioned wells so water table data would show the direction and magnitude of groundwater flow from fields to ditches or the Manokin River. The northern portion of the farm is drained by two PDA ditches (~3 m [10 ft] deep) and one shallow field ditch (~1 m [3 ft] deep) that run east to west and empty directly into the Manokin River (figure 1). In the monitored area, two shallow ditches run south to north and empty into a PDA ditch. The southern portion of the farm is drained by three, parallel shallow field ditches (0 to 1 m [0 to 3 ft] deep) running east to west and emptying into a deeper (~1 to 2 m [3 to 6 ft] deep) collection ditch (figure 1). The collection ditch drains south into a deep PDA ditch (3 to 4 m [10 to 13 ft] deep) that empties into the Manokin River.

We designed wells so we could only measure depth to the water table (n = 5; wells 2, 6, 14, 15, 24) or both measure water table depth and collect groundwater samples for N and P analysis (n = 21; all other wells). All wells consisted of a 5 cm (2 in) diameter, PVC pipe screened with thin slits over its entire length. We installed wells by drilling a hole of the same diameter in the soil and inserting the screened PVC pipe. We installed wells to ~3 m (10 ft), which was as deep as the lowest expected water tables. We inserted devices into the 21 groundwater sampling wells so we could collect samples from discrete depths in the soil profile (figure 2). Discrete-depth sampling devices consisted of an outermost, solid, 3.75 cm (1.5 in) diameter PVC pipe, on which we glued a series of rubber K-packers (Dean Bennet Supply, Denver, Colorado). We sealed the bottom of the solid pipe with a cap so no groundwater could penetrate inside the pipe. The K-packers slipped directly on the outside of the PVC pipe. They had three rubber ribs and formed a water-tight seal between the smaller pipe on which they were attached and the larger well casing into which the smaller pipe was inserted. Thus, water entering a well in a section between two K-packers could not mix with water entering well sections above or below (figure 2). Our initial laboratory tests confirmed that the K-packers did indeed create a water-tight seal. At the bottom of specific pipe sections between K-packers, we drilled sampling ports and fit rubber grommets into the holes. We ran plastic tubing from the ports to the top of the pipe and sealed any gaps between the grommets and tubing. We then inserted a second solid PVC pipe inside the first pipe so that it ran through the pipe cap into the screened well section beneath it (figure 2). This construction allowed groundwater entering screened wells below the sampling device to rise up the innermost PVC tube to a height equal to the water table. Thus in the same well, we could both measure depth to groundwater and collect groundwater samples at discrete depths for N and P analysis. With the design of these wells, we were not measuring the water table per se, but rather the hydraulic head at the bottom of wells.

Well sampling devices were either 1.5 or 2.4 m (5 or 8 ft) long. The 1.5 m (5 ft) wells had three sampling depths—from 0 to 30, 45 to 75, and 90 to 140 cm (0 to 12, 18 to 30, and 36 to 56 in)—and were in field centers and

Figure 2
Schematic of the groundwater wells with discrete-depth sampling devices.



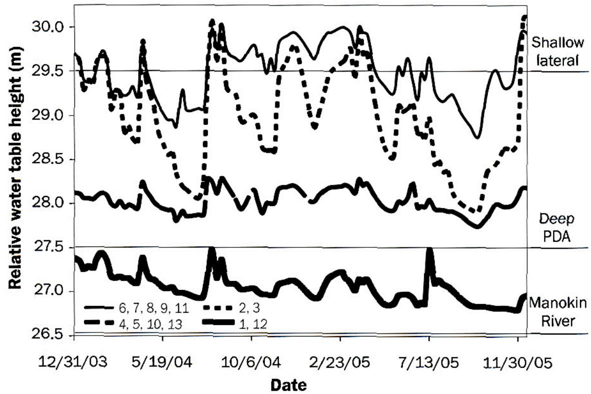
next to shallow ditches where we expected higher water tables. Wells 25 and 26 in a field center had four sampling depths—from 0 to 20, 35 to 60, 75 to 100, and 115 to 140 cm (0 to 8, 14 to 24, 30 to 40, and 46 to 56 in). The 2.4 m (8 ft) wells had four sampling depths—from 0 to 30, 45 to 75, 90 to 135, and 150 to 235 cm (0 to 12, 18 to 30, 36 to 56, and 60 to 94 in)—and were next to collection and PDA ditches where we expected deeper water tables. When sampling, we attached tubing from all well depths to a peristaltic pump and simultaneously pumped all tubes. This ensured groundwater flowed only laterally into wells at the discrete depths (Kaleris et al. 1995). Some rainfall simulation experiments with the wells showed that as water tables were rising, groundwater nutrient concentrations from sampling depths below the initial water table did not change, while concentrations above the water table were greater and changed as water tables rose. Thus, our well design did indeed result in only lateral groundwater flow at discrete depths.

Specific sampling depths ensured we could sample groundwater deeper than all shallow ditches and slightly deeper than collection and PDA ditches. We could thus assess N and P transport from fields to all ditches. Discrete sampling also allowed greater scrutiny of differential groundwater N and P concentrations with depth (Delin and Landon 1996; Graham and Downey 1992). Consistent patterns of differential concentrations through time could help reveal chemical or physical mechanisms controlling subsurface N and P transport.

Next to two field-center wells (7, 19) and three ditch-adjacent wells (5, 8, 17), we also installed shallow piezometers to investigate the possibility of perched water tables. A piezometer consisted of a 5 cm (2 in) diameter, 75 cm (30 in) long PVC pipe that was screened with thin slits over its bottom 30 cm (12 in) and sealed at the bottom. We installed piezometers by drilling a hole of the same diameter in the soil and inserting the PVC pipe. Even though they would at times go dry, we installed piezometers to only 75 cm (30 in) to ensure that their bottoms were above the clay layer in soils and that we were measuring the hydraulic head above the clay layer. Monitoring wells would measure hydraulic head below the clay layer. A greater hydraulic head in piezometers would indicate a perched water table above the clay layer. Existence of the perched water table would provide initial evidence of relatively rapid lateral groundwater flow and nutrient transport along the top of the clay layer to ditches (Reuter et al. 1998; Walter et al. 2000).

Figure 3

Weekly water table data from December 2003 to December 2005 for wells on the northern half of the farm.

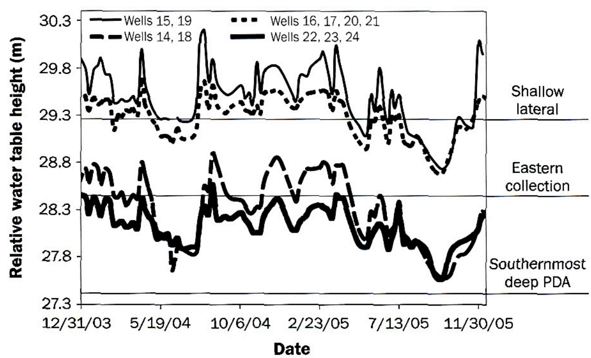


Notes: Data from wells with similar water table elevations are averaged for clarity. The approximate depth of shallow field ditches, deep Public Drainage Association ditches, and the Manokin River are indicated.

Hydrology and Water Quality Monitoring. We manually measured depth to water table

Figure 4

Weekly water table data from December 2003 to December 2005 for wells on the southern half of the farm.



Notes: Data from wells with similar water table elevations are averaged for clarity. The approximate depth of shallow field, collection, and deep Public Drainage Association ditches are indicated.

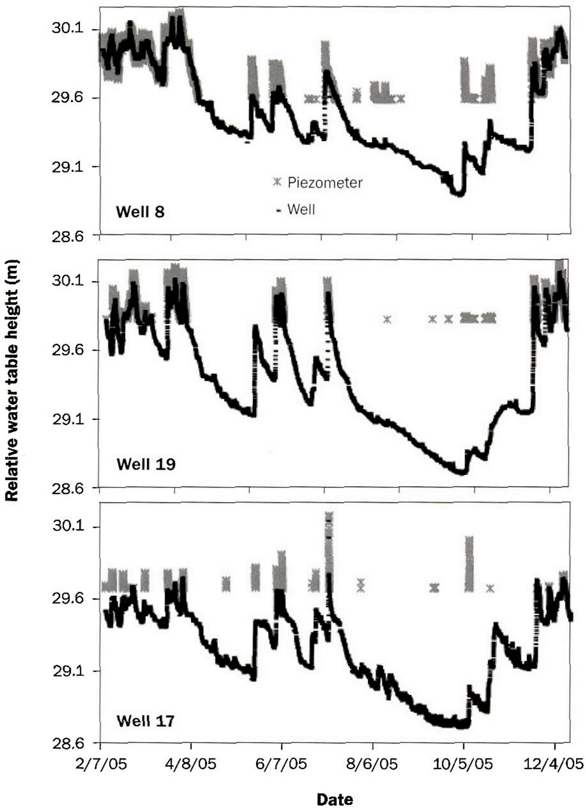
in all wells weekly from November 2003 to February 2006. In June 2004, in wells 5 to 8, 15 to 19, and all piezometers, we installed automated water level recording devices that measured water table depth in wells every 15 minutes. Automated data allowed us to determine the nature of water table fluctuations in response to rain and drainage and to detect the occurrence of perched water tables. This would help determine when and how long water and nutrients might be flowing to shallow ditches.

We sampled groundwater monthly in all 21 sampling wells from November 2003 to February 2006. When collecting samples, we let water flow for 5 minutes to purge tubes and ensure we were collecting fresh groundwater samples. We collected approximately 250 ml (8.5 fl. oz.) for each sample and filtered samples within 24 hours through 0.45 µm (17.7 micro-in) filters and stored them at 4°C (39°F) until analysis. We analyzed samples for NO_3-N by flow injection analysis using a Lachat autoanalyzer (Quick Chem FIA+ 8000 Series, Lachat Instruments, Loveland, Colorado) and the method of Wendt (2000) and dissolved P colorimetrically by the method of Murphy and Riley (1962). Monthly samples represented groundwater N and P concentrations that were in chemical equilibrium with soil. We also sampled wells 9 to 12 and 17 to 20 within 48 hours after rainfalls greater than 1.25 cm (0.5 in); we sampled wells 25 and 26 during storms when possible, but more typically immediately after storms and then every 8 to 12 hours for the next 24 to 48 hours. More frequent storm samples represented groundwater N and P concentrations that recently leached through topsoils and may not have reached equilibrium with soils.

Soil Sampling and Analysis. In December 2005, we collected intact soil cores adjacent to all sampling wells to depths of 2 m (6 ft). We sectioned cores and collected all soil from the same depths as discrete-depth groundwater sampling. We air-dried soil samples and ground them to pass a 2 mm (0.08 in) sieve. We analyzed all soils for Mehlich-3 P (Mehlich 1984).

Figure 5

Water level data for wells 8, 17, and 19 and their adjacent piezometers.



Notes: Piezometer data are shown only when piezometers were not dried out. Higher water levels for piezometers than wells indicate perched water tables.

Results and Discussion

Hydrology. In the northern portion of the farm, water tables in one field center (wells 6 to 11) fluctuated above and below shallow field ditches, but were always higher than deep PDA ditches or the Manokin River (figure 3). Thus, groundwater may flow from this field to shallow ditches only intermittently, and the ditches may often dry out and lose hydraulic connection with groundwater. During drier times, water will instead flow to deeper PDA ditches or Manokin River. Water tables in the field with wells 2 and 3 were most often below the shallow ditch to the north but always above the deep PDA ditch and the Manokin River bordering the field. Thus, groundwater from this field may flow more east and south to the deep ditch and Manokin River than north into the shallow ditch. Because water tables were always higher than deep ditches and the Manokin River, groundwater flow to deep ditches and the Manokin River was continuous through time.

Hydrology was similar in the southern portion of the farm (figure 4). Water tables in the center (wells 15 and 19) and along the edges (wells 14, 16, 17, 18, 20, and 21) of the

Table 1

The range and average dissolved P and NO_3-N concentrations and number of samples taken for four different sampling depths as compiled across 21 sampling wells from December 2003 through March 2006.

	Dissolved P			NO_3-N		
Sampling depth	Range (mg L^{-1})	Average (mg L^{-1})	*n*	Range (mg L^{-1})	Average (mg L^{-1})	*n*
0 to 30 cm	0.01 to 4.60	0.65	27	0.20 to 39.30	9.7	24
45 to 75 cm	0.00 to 12.30	0.53	186	0.01 to 54.80	9.4	159
90 to 135 cm	0.00 to 7.40	0.14	297	0.06 to 59.10	14.2	257
150 to 235 cm	0.00 to 0.17	0.03	70	3.10 to 38.20	18.4	65

two fields between the shallow ditches fluctuated above and below the shallow ditches and the eastern collection ditch. However, water tables were always higher than deep PDA ditches to the north or south (wells 13, 22, 23, and 24). Groundwater may thus flow to the collection ditch and shallow field ditches only intermittently, and the ditches may dry out and lose hydraulic connection with groundwater. During drier times, groundwater will flow either north or south to deep PDA ditches. Water levels in wells 22, 23, and 24 in the southern field were nearly always below shallow ditches or the eastern collection ditch, but always higher than the southernmost PDA ditch. Thus, groundwater from this field flows continuously to the deep PDA ditch and not to other ditches.

Water tables rose rapidly in response to rain (see figure 7 as an example for two field-center wells, as discussed later), but drained back from 15 to 60 cm (6 to 24 in) the first day after rain. Nutrient transport may be greatest during rapid drainage because groundwater rises into nutrient-rich topsoils and because groundwater travel times and distances decrease as nearby shallow ditches become active (DeWalle 1994). After the first day, the rate of water table fall decreased. At 5 days after rain, water table fall ranged from 1 to 10 cm (0.4 to 4.0 in) per day. At ten days after rain, water fall ranged from 1 to 5 cm (0.4 to 2.0 in) per day. Nutrient transport may be less during slower drainage because shallow ditches become inactive and groundwater must travel farther and longer to deep ditches. This presumably allows soils to adsorb more nutrients from groundwater, especially for P, as discussed later.

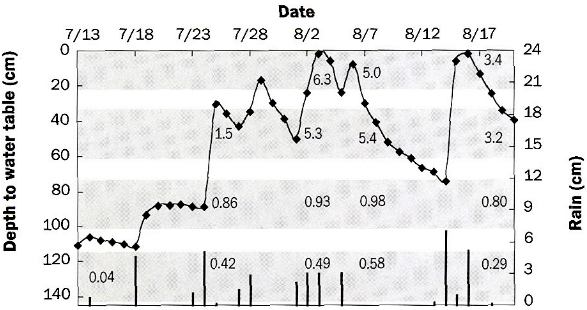
Figure 5 shows continuous water table data from three pairs of wells and piezometers (8, 19, and 17) that had long periods of record. Wells 8 and 17 were next to shallow field ditches, and well 19 was at a field center. Water levels were often higher in piezometers than in wells, showing that water tables did periodically perch (assumedly on top of subsoil clay horizons), but perching typically persisted for only 24 to 48 hours. Perched water either infiltrated through restrictive layers or drained laterally to ditches. Lateral drainage on top of restrictive clay horizons may result in greater nutrient transport than infiltration through these horizons (Reuter et al. 1998; Walter et al. 2000).

Groundwater Nutrient Concentrations: Nitrogen. For 540 groundwater samples, NO_3-N concentrations ranged from 0.01 to 59.1 mg L^{-1} (0.0000013 to 0.0079 oz gal^{-1}) and exceeded the United States Environmental Protection Agency (USEPA) 10 mg L^{-1} (0.0013 oz gal^{-1}) drinking water standard in 54% of all samples. These concentrations are similar to those observed by Staver and Brinsfield (1998) and Sims et al. (1996) in Maryland and Delaware coastal plain soils. Every well had concentrations of NO_3-N greater than 10 mg L^{-1} (0.0013 oz gal^{-1}) on at least one sampling date. In individual wells, 6% to 100% of samples collected had NO_3-N concentrations greater than 10 mg L^{-1} (0.0013 oz gal^{-1}). In 14 of the 21 sampling wells (3 to 5, 7 to 12, 18, 19, 22, and 23) that were located at both field centers and ditch edges, NO_3-N concentrations were predominately greater than 10 mg L^{-1} (0.0013 oz gal^{-1}). Of the 350 samples from these 14 wells, 80% had NO_3-N concentrations greater than 10 mg L^{-1} (0.0013 oz gal^{-1}). In the remaining wells, only 10 samples had NO_3-N concentrations greater than 10 mg L^{-1} (0.0013 oz gal^{-1}). For all wells, NO_3-N concentrations tended to increase with depth in the soil (table 1), demonstrating the ability of N to leach through soil profiles. There was no apparent pattern to changes in groundwater NO_3-N concentrations from one sampling time to another. It is clear from these data that soil and hydrology conditions and management practices on the farm support widespread NO_3-N transport in groundwater. Environmentally important N loss through groundwater flow from this and similar farms in the region is probable.

Groundwater Nutrient Concentrations: Phosphorus. There is no regulatory standard for groundwater dissolved P concentrations. However, 0.2 mg L^{-1} (0.000027 oz gal^{-1}) is about the concentration required in the soil solution for crop growth (Tisdale et al. 1993), double the USEPA recommended 0.1 mg L^{-1} (0.000013 oz gal^{-1}) concentration limit for total P in streams, but less than the 1.0 mg L^{-1} (0.00013 oz gal^{-1}) total P USEPA standard for wastewater effluent. To more clearly present results in this paper, we thus used 0.2 mg L^{-1} (0.000027 oz gal^{-1}) to represent a lower limit for ground-water P concentrations that would adversely affect water quality if delivered to surface waters. For 620 groundwater samples, dissolved P concentrations ranged from 0.0 to a very high 12.3 mg L^{-1} (0.0 to 0.0016 oz gal^{-1}), which was collected at a depth of 45 to 75 cm (18 to 30 in). Groundwater P exceeded 0.2 mg L^{-1} (0.000027 oz gal^{-1}) in only 15% of all samples and in only 11 wells. Groundwater P concentrations were generally greatest in topsoils and decreased with depth (table 1), but dissolved P as great as 7.4 mg L^{-1} (0.00098 oz gal^{-1}) existed as deep as one meter. These high P concentrations are of a magnitude similar to those observed by Nelson et al. (2005) at depths of 45 and 90 cm (18 and 36 in) in two P-enriched soils in the North Carolina coastal plain. These data clearly show that groundwater P transport around the farm was not as ubiquitous as for NO_3-N. The following discussion explores how soil chemistry and hydrology may have affected dissolved P movement in groundwater.

Data for wells 25 and 26, which were in field centers and were sampled frequently after rain storms, suggest a mechanism for soil P mobilization into groundwater. The soil profile around wells 25 and 26 was very enriched in Mehlich-3 P (400 mg kg^{-1} [0.0064 oz lb^{-1}] from 0 to 20 cm [0 to 8 in], 200 mg kg^{-1} [0.0032 oz lb^{-1}] from 20 to 40 cm [8 to 16 in], and 40 mg kg^{-1} [0.00064 oz lb^{-1}] from 40 to 60 cm [16 to 24 in]). These soil P data suggest a high potential to mobilize P in groundwater and that the greatest source of P is topsoil. Figure 6 shows water table and

Figure 6
Water table and groundwater dissolved P data for wells 25 and 26 from July 13 to August 20, 2004.



Note: Gray horizontal bars represent depths in the soil profile from which groundwater samples were taken. Values in the gray horizontal bars are dissolved P concentrations measured from those depths at different dates. The black line represents depth to water table for the period. Black vertical bars represent depths of rain for individual days.

groundwater P data for the two wells from July 13 to August 20, 2004. During this 38-day period, water tables started at about 110 cm (44 in) deep, where groundwater P was 0.04 mg L^{-1} (0.0000053 oz gal^{-1}). Two storms in July raised water tables to about 30 cm (8 in) and increased groundwater P throughout the soil profile to concentrations that were about an order of magnitude greater than what long-term sampling suggests are P concentrations in equilibrium with soil (0.2 mg L^{-1} [0.000027 oz gal^{-1}] from 30 to 60 cm [12 to 24 in], 0.1 mg L^{-1} [0.000013 oz gal^{-1}] from 70 to 100 cm [28 to 40 in], and 0.04 mg L^{-1} [0.0000053 oz gal^{-1}] from 120 to 140 cm [48 to 56 in]). Because topsoils around these wells had the most P, the source of elevated groundwater P was most likely from rain leaching P from topsoils through the soil profile.

Figure 6 shows that from the end of July onward, frequent rain kept water tables above about 60 cm (23.6 in), where groundwater P concentrations ranged from 3.2 to 6.3 mg L^{-1} (0.00043 to 0.00084 oz gal^{-1}). In comparison, surface runoff collected on August 4, 2004, had a similar dissolved P concentration of 3.9 mg L^{-1} (0.00052 oz gal^{-1}) (see Kleinman et al. 2007). Because the deepest two sampling depths remained below the water table, they were presumably not further influenced by P leaching from the topsoil. However, groundwater P from these sampling depths remained elevated for almost a month. Overall, these data suggest that rain storms can mobilize soil P into groundwater to concentrations much greater than those in equilibrium with soil. Rain can also leach P down through the soil profile, and groundwater P concentrations at depths as great as 120 to 140 cm (48 to 56 in) can remain elevated for days or even weeks. Figure 7 shows groundwater P concentrations in several wells around the farm were consistently greatest shortly after storms and decreased with time, and they were often as great as 1 to 4 mg L^{-1} (0.00013 to 0.00053 oz gal^{-1}) at depths greater than 50 cm (20 in). Once P is mobilized in groundwater, soil will re-adsorb P over time, but complete re-adsorption may apparently take a week or more. Phosphorus mobilized in groundwater can potentially be delivered to ditches during this re-adsorption period.

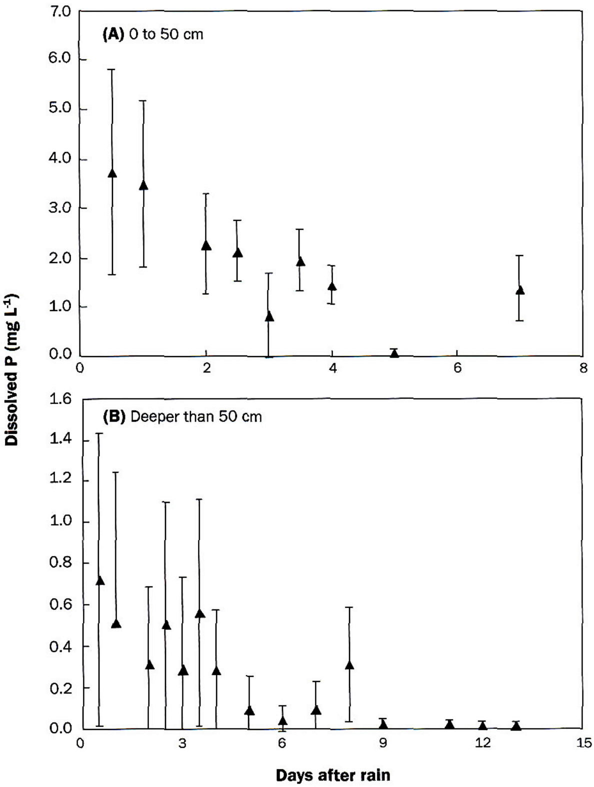
While the above data for wells 25 and 26 show a mechanism for P mobilization in groundwater, other data show the degree of P mobilization can vary. In five (7, 11, 19, 25, and 26) of the field-center wells, 60% of 430 groundwater samples had P concentrations greater than 0.2 mg L^{-1} [0.000027 oz gal^{-1}]). Only wells 3 and 23 were exceptions, but this was more likely due to very few samples able to be collected (only eight during more than two years). Some of the five field-center wells had greater P concentrations than others. For example, wells 7, 11, and 19 had similar soil P concentrations, which suggests a similar potential to mobilize P in groundwater. However, average groundwater P concentrations were greatest in well 7 (1.9 mg L^{-1} [0.00025 oz gal^{-1}]), followed by well 11 (1.3 mg L^{-1} [0.00017 oz gal^{-1}]), and then well 19 (0.2 mg L^{-1} [0.000027 oz gal^{-1}]). Well 7 also had more samples with groundwater P concentrations greater than 0.2 mg L^{-1} (0.000027 oz gal^{-1}) (75%) than well 11 (43%) or well 19 (31%). Figure 8 shows water tables were generally highest and rose most often into P-enriched topsoils in well 7, followed by well 11 and then well 19. Therefore, P mobilization into groundwater may increase with the frequency or duration of water tables rise into P-enriched topsoils.

In contrast to field-center wells, only three (12, 18, and 21) out of 14 wells adjacent to ditches or the Manokin River had groundwater P concentrations consistently greater than 0.2 mg L^{-1} (0.000027 oz gal^{-1}). Soil P was a major difference between hydrologically similar field-center wells that had high groundwater P concentrations and ditch-adjacent wells that did not. Field-center wells had an average Mehlich-3 soil P of 450 mg kg^{-1} (0.0072 oz lb^{-1}) from 0 to 20 cm (0 to 8 in), 380 mg kg^{-1} (0.0061 oz lb^{-1}) from 20 to 40 cm (8 to 16 in), and 40 mg kg^{-1} (0.00064 oz lb^{-1}) from 40 to 60 cm (16 to 24 in). At the same depths in ditch-adjacent well profiles, soil Mehlich-3 P was 290, 141, and 7 mg kg^{-1} (0.0046, 0.0023, and 0.00011 oz lb^{-1}). Overall, data from field-center and ditch-adjacent wells show the greatest amount of soil P was mobilized into groundwater when high water table hydrology combined with excessive soil P. When soil P was less or water tables were deeper, less P was mobilized in groundwater.

Data from field-center wells clearly show considerable P was mobilized in groundwater during storms, thus providing at least a potential for groundwater P delivery to ditches. In evaluating surface runoff and ditch nutrient export data, Kleinman et al. (2007) also conclude groundwater was a significant contributor of P to ditches on the farm. For our data, we looked at groundwater P concentrations in ditch-adjacent wells as the most concrete evidence for groundwater P delivery to ditches. Greater groundwater P concentrations in field-center wells than ditch-adjacent wells (as described above) suggests more P was mobilized in groundwater in fields during storms than was actually delivered to ditches. However, close examination of hydrology and groundwater P data from ditch-adjacent wells provides evidence

Figure 7

Groundwater dissolved P concentrations for several wells where samples consistently had groundwater P concentrations greater than 0.2 mg L^{-1}, plotted against when groundwater samples were collected relative to days after a rain event.



Note: Data are separated into sample depths (A) above 50 cm in the soil and (B) below 50 cm.

for P delivery to ditches. It also suggests variations in drainage hydrology and soil properties may have controlled the extent of P delivery.

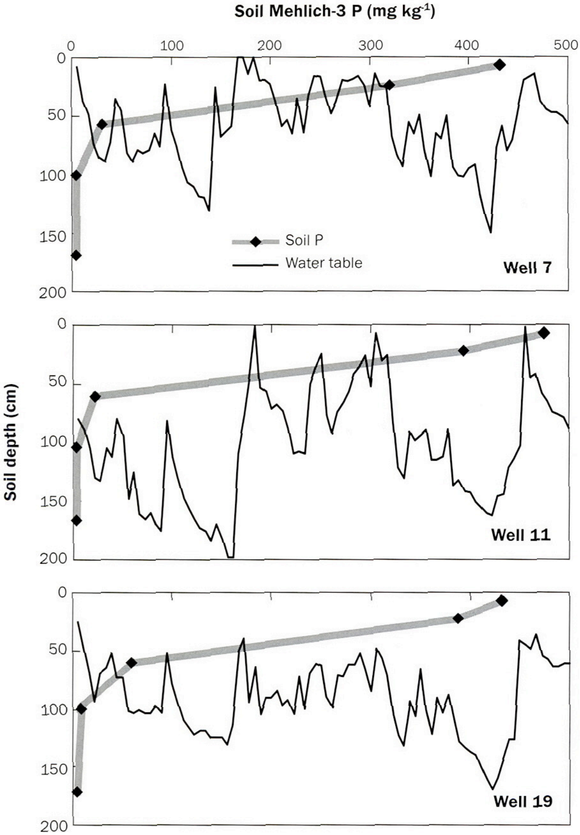
For all six wells adjacent to shallow field ditches, there was a strong relationship between average soil P content (mg kg^{-1}) from 0 to 75 cm (0 to 30 in) deep and average groundwater P concentrations (mg L^{-1}) during the two years of sampling (groundwater P = 0.0003 × soil P + 0.017, r^2 = 0.93). Because water tables fluctuated above and below shallow ditches, water flow to these ditches was intermittent and likely from only near-ditch zones. Thus, P delivery to shallow ditches was apparently controlled more by near-ditch soil P conditions. This suggests that limiting soil P accumulation in near-ditch zones might help reduce groundwater P delivery to shallow ditches.

Because water tables were always higher than deep ditches or the Manokin River, the magnitude and duration of groundwater flow to deep ditches was likely greater than to shallow ditches. Therefore, water flow to deep ditches or the Manokin River was from more than just near-ditch zones, and P delivery to these ditches might be controlled by more than just near-ditch soil P conditions. For example, soil P concentrations were least around well 12 next to the Manokin River, greater around well 18 next to a collection ditch, and greatest around well 10 next to a deep PDA ditch (figure 9). However, average groundwater P concentrations were greatest in well 12 (0.79 mg L^{-1} [0.00011 oz gal^{-1}]), less in well 18 (0.09 mg L^{-1} [0.000012 oz gal^{-1}]), and least in well 10 (0.02 mg L^{-1} [0.0000027 oz gal^{-1}]). Therefore, near-ditch soil P conditions apparently did not control P delivery to these ditches. Instead, there appeared to be a better relationship between groundwater P concentrations and the depth in the soil where groundwater typically flowed. Water tables fluctuated between 50 and 100 cm (19.7 to 39.4 in) below the soil surface in well 12, between 100 and 200 cm (39.4 and 78.7 in) in well 18, and between 200 and 300 cm (78.7 and 118.1 in) in well 10 (figure 9). Deeper water flow suggests longer flow paths from fields to ditches and a greater potential for subsoils to adsorb P out of groundwater. Nelson et al. (2005) also observed that low-P subsoils in the North Carolina coastal plain were able to adsorb P out of the soil solution. Therefore, increasing the length of groundwater flowpaths through low-P subsoils may reduce groundwater P delivery to deep ditches or the Manokin River.

Data from well 12 next to the Manokin River provide the most compelling evidence for P delivery to ditches or the Manokin. Soil P in the topsoil around well 12 (figure 9) was not enriched compared to field centers, suggesting a limited potential for P mobilization in groundwater. However, groundwater P concentrations exceeded 0.2 mg L^{-1} (0.000027 oz gal^{-1}) in 70% of samples. Furthermore, soil P was 50 mg kg^{-1} (0.0008 oz lb^{-1}) at the depth of 60 cm (23.6 in) and 30 mg kg^{-1} (0.00048 oz lb^{-1}) at the depth of 100 cm (39.4 in), even though soil P in the topsoils was only 150 mg kg^{-1} (0.0024 oz lb^{-1}). Comparatively, around four other wells (2, 3, 5, and 17) where topsoil P was about 150 mg kg^{-1} (0.0024 oz lb^{-1}), soil P at 60 and 100 cm was less than 10 mg kg^{-1} (0.00016 oz lb^{-1}). This suggests that soil P enrichment deeper

Figure 8

Vertical distribution of Mehlich-3 P in the soil profiles of wells 7, 11, and 19, along with weekly depth to water table data from December 2003 through February 2006.



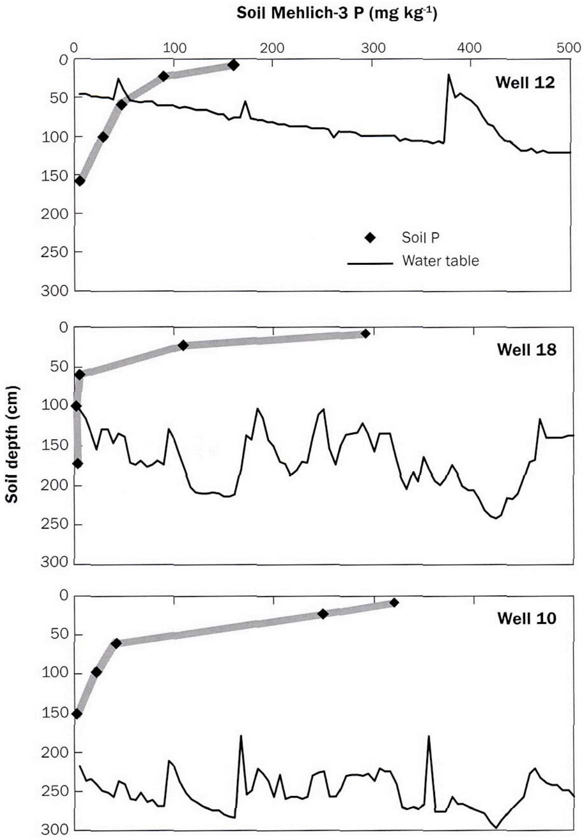
in the profile around well 12 was greater than what leaching of P down from the topsoil might have caused. The hydrology, soil P, and groundwater P characteristics from well 12 combined thus suggest that P mobilized in groundwater from the field to the east may indeed be moving past well 12 into the Manokin River. Furthermore, in the 70% of groundwater P samples that exceeded 0.2 mg L^{-1} (0.000027 oz gal^{-1}), P concentrations ranged from only 0.6 to 1.5 mg L^{-1} (0.00008 to 0.0002 oz gal^{-1}) regardless of sampling date. This suggests a consistent source of relatively high groundwater P concentrations being delivered to the Manokin River.

Summary and Conclusions

We monitored groundwater hydrology and N and P concentrations during more than two years on a heavily ditch-drained, poultry-grain farm on Maryland's Lower Eastern Shore. Water tables in field centers fluctuated above and below shallow ditches, but were always higher than deep PDA ditches or the Manokin River. Thus, groundwater flow to shallow ditches is only intermittent, and shallow ditches may often dry out and lose hydraulic connection with groundwater. During drier times, water will instead flow to deep ditches or Manokin River. All water tables were always higher than the bottom of deep ditches and the Manokin River. Thus groundwater flow to deep ditches and the Manokin River was continuous through time. Water tables rose rapidly in response to rain, but drained back from 15 to 60 cm (6 to 24 in) the first day after rain. The rate of water table decline decreased rapidly thereafter. Data show perched water tables did occur fairly frequently, most likely on top of restrictive subsoil clay horizons. Although perching persisted for only 24 to 48 hours, groundwater nutrient transport could be accelerated if rapid, lateral movement of perched water to ditches occurs.

Data reveal NO_3-N can move readily in groundwater in high concentrations (>10 mg L^{-1} [>0.0013 oz gal^{-1}]) throughout the farm. Therefore, loss of N through subsurface groundwater flow from this and similar poultry-grain farms in the region is probable. While very high concentrations of dissolved P existed in groundwater, P transport in groundwater was restricted compared to NO_3-N. During storms, rain infiltrating though high P topsoils was able to mobilize soil P into groundwater and move considerably high concentrations of this mobilized P as deep as 1.5 m (4 ft). These elevated groundwater P concentrations persisted for days or even weeks. High groundwater P concentrations occurred in essentially all field centers, but were greatest where high water table hydrology combined with the greatest soil P concentrations. When water tables were deeper or soil P was not as great, groundwater P concentrations were less. Data also suggest P mobilized in groundwater can be delivered to ditches or the Manokin River. Phosphorus delivery to shallow ditches was apparently controlled by near-ditch soil P conditions, while P delivery to deep ditches or the Manokin River was controlled by how deep in subsoils groundwater flowed. Therefore, limiting soil P accumulation in near-ditch zones may help reduce P delivery to shallow ditches, and increasing the length of groundwater flowpaths through low-P subsoils that can adsorb P may help reduce

Figure 9
Vertical distribution of Mehlich-3 P in the soil profiles of wells 12, 18, and 10, along with weekly depth to water table data from December 2003 through February 2006.



P delivery to deep ditches or the Manokin River. Future field and modeling work at the site will attempt to more firmly demonstrate and quantify groundwater nutrient transport and delivery to ditches, especially for P.

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References

Boesch, D.F., R.B. Brinsfield, and R.E. Magnien. 2001. Chesapeake Bay eutrophication: scientific understanding, ecosystem restoration, and challenges for agriculture. Journal of Environmental Quality 30:303-320.

Boynton, W.R. 2000. Impact of nutrient inflows on Chesapeake Bay. *In* Agriculture and Phosphorus Management: The Chesapeake Bay, ed. A.N. Sharpley, 23-40. Boca Raton, FL: Lewis Publishers.

Butler, J.S., and F.J. Coale. 2005. Phosphorus leaching in manure-amended Atlantic Coastal Plain soils. Journal of Environmental Quality 34: 370-381.

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological Applications 8:559-568.

Coale, F.J., J.T. Sims, and A.B. Leytem. 2002. Accelerated deployment of an agricultural nutrient management tool: The Maryland Phosphorus Site Index. Journal of Environmental Quality 31: 1471-1476.

Delin, G.N., and M.K. Landon. 1996. Multiport well design for sampling of ground water at closely spaced vertical intervals. Ground Water 34:1098-1104.

DeWalle, D.R., and H.B. Pionke. 1994. Streamflow generation on a small agricultural catchment during autumn recharge. II. Stormflow periods. Journal of Hydrology 163:23-42.

Graham, W.D., and D. Downey. 1992. A comparison of water quality information obtained from depth-integrated versus depth-specific groundwater monitoring devices. Soil and Crop Science Society of Florida Proceedings 51: 58-63.

Kaleris, V., C. Hadjitheodorou, and A.C. Demetracopoulos. 1995. Numerical simulation of field methods for estimating hydraulic conductivity and concentration profiles. Journal of Hydrology 171:319-353.

Kleinman, P.J.A., A.L. Allen, B.A. Needelman, A.N. Sharpley, P.A. Vadas, L.S. Saporito, G.J. Folmar, and R.B. Bryant. 2007. Dynamics of phosphorus transfers from heavily manured Coastal Plain soils to drainage ditches. Journal of Soil and Water Conservation 62(4):225-235.

Malhi, S.S., J.T. Harapiak, R. Karamanos, K.S. Gill, and N. Flore. 2003. Distribution of acid extractable P and exchangeable K in a grassland soil as affected by long-term surface application of N, P, and K fertilizers. Nutrient Cycling in Agroecosystems 67:265-272.

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Communications in Soil Science and Plant Analysis 15:1409-1416.

Mozafarri, M., and J.T. Sims. 1994. Phosphorus availability and sorption in an Atlantic Coastal Plain watershed dominated by animal based agriculture. Soil Science 157: 97-107.

Murphy L.J., and Riley J.P. 1962. A modified single solution method for determination of phosphate in natural waters. Analytica Chimica Acta 27: 31-33.

Nelson, N.O., J.E. Parsons, and R.L. Mikkelsen. 2005. Field-scale evaluation of phosphorus leaching in acid sandy soils receiving swine waste. Journal of Environmental Quality 34:2024-2035.

Rechcigal, J.E., R.B. Reneau, and D.E. Starner. 1985. Movement of subsurface fertilizer and limestone under irrigated and non-irrigated conditions. Soil Science 140:442-448.

Reuter, R.J., P.A. McDaniel, J.E. Hammel, and A.L. Falen. 1998. Solute transport in seasonal perched water tables in loess-derived soilscapes. Soil Science Society of America Journal 62:977-983.

Sallade, Y.E., and J.T. Sims. 1997a. Phosphorus transformations in the sediments of Delaware's agricultural drainageways. I. Phosphorus forms and sorption. Journal of Environmental Quality 26:1571-1579.

Sallade, Y.E., and J.T. Sims. 1997b. Phosphorus transformations in the sediments of Delaware's agricultural drainageways. II. Effects of reducing conditions on phosphorus release. Journal of Environmental Quality 26:1579-1588.

Schmidt, J.P., C.J. Dell, P.A. Vadas, and A.L. Allen. 2007. Nitrogen export from Coastal Plain field ditches. Journal of Soil and Water Conservation 62(4):235-243.

Shirmohammadi, A., R. D. Wenberg, W. F. Ritter, and F. S. Wright. 1995. Effect of agricultural drainage on water quality in Mid-Atlantic states. Journal of Irrigation and Drainage Engineering 121:302-306.
Sims, J.T., and D.C. Wolf. 1993. Poultry waste management: Agricultural and environmental issues. Advances in Agronomy 52:1-81.
Sims, J.T., A.S. Andres, J.M. Denver, and W.J. Gangloff. 1996. Assessing the impact of agricultural drainage on ground and surface water quality in Delaware. Final Project Report. Dover, DE: Delaware Department of Natural Resources and Environmental Control.
Sims, J.T., and K.L Gardey. 1996. The phosphorus index: A phosphorus management strategy for Delaware's agricultural soils. Soil Testing Program Factsheet ST-05. University of Delaware.
Sims, J.T., R.R. Simard, and B.C. Joern. 1998. Phosphorus loss in agricultural drainage: Historical perspective and current research. Journal of Environmental Quality 27:277-293.
Staver, K.W., and R.B. Brinsfield. 1998. Using cereal grain winter cover crops to reduce groundwater nitrate contamination in the mid-Atlantic coastal plain. Journal of Soil and Water Conservation 53:230-240.
Thomas, D.L., C.D. Perryy, R.O Evans, F.T. Izuno, K.C. Stone, and J.W. Gilliam. 1995. Agricultural drainage effects on water quality in southeastern U.S. Journal of Irrigation and Drainage Engineering 121(4):277-282.
Tisdale, S.L., W.L. Nelson, J.D. Beaton, and J.L. Havlin. 1993. Soil fertility and fertilizers. Macmillan Publishing Company, New York, NY.
Walter, M. T., J.S. Kim, T.S. Steenhuis, J.Y. Parlange, A. Heilig, R.D. Braddock, J.S. Selker, and J. Boll. 2000. Funneled flow mechanisms in a sloping layered soil: Laboratory investigation. Water Resources Research 36:841-849.
Weld, J.L., D.B Beegle, J.T. Sims, J.L. Lemunyon, A.N. Sharpley, W.J. Gburek, F.C Coale and A.B. Leytem. 2000. Comparison of state approaches to the development of phosphorus indices. *In* 2000 Agronomy abstracts, 329. Madison, WI: American Society of Agronomy-Crop Science Society of America-Soil Science Society of America.
Wendt, K. 2000. Determination of nitrate/nitrite in surface wastewaters by flow injection analysis. QuickChem Method 10-107-04-1-A FIA Methodology. Loveland, CO: Lachat Instruments.

Managing natural processes in drainage ditches for nonpoint source nitrogen control

J.S. Strock, C.J. Dell, and J.P. Schmidt

Abstract: In watersheds dominated by agriculture, artificial drainage systems can efficiently and quickly transport excess water from agricultural soils. The application of more nitrogen (N) than a crop uses creates a surplus in the soil and increases the risk of N loss to the environment. We examine issues associated with agricultural N use, N transfer from artificially drained agricultural land to drainage ditches, N cycling within ditches, and options for management. Watercourses in agricultural watersheds often have high concentrations of N and are effectively N saturated. Numerous processes are involved in N cycling dynamics and transport pathways in aquatic ecosystems including N mineralization, nitrification, and denitrification. Flow control structures can lower N losses related to artificial drainage by increasing water retention time and allowing greater N removal. An ongoing study in Minnesota compares the impact of flow control structures on N losses from paired ditches with and without flow control. During the first year of observation, results were mixed, with lower N concentrations in nonstorm event samples from the ditch with the flow control structure, but no significant difference in annual total N load between the two ditches. Appropriate management of drainage ditches represents a potential opportunity to remove biologically available forms of N from drainage water through a combination of physical and biogeochemical processes.

Key words: ditch—nitrate—nitrogen—total nitrogen—water quality

Artificial drainage can increase crop yields, reduce risk of saturated soil at planting and harvest, and improve economic returns for crop producers in many regions of the United States (Pavelis 1987). Starting in the late 1700s, drainage in the United States has been improved by constructing open channel ditches (frequently by artificially deepening and straightening natural waterways) and by installing subsurface tiles that transfer excess water to ditches or natural waterways. In the regions with slowly permeable soils, like much of the Midwest, extensive networks of subsurface tile drains and vegetated ditches have been established. In other regions, such as the Delmarva Peninsula, which have highly permeable soils but also high regional water tables, improved drainage can be obtained using only open channel ditches.

Artificial drainage can considerably increase the amounts of sediment, nutrients, pathogens, and pesticides exported from agricultural fields to waterways (Gilliam et al. 1999; Randall and Goss 2001). One of the most significant water quality impairments within aquatic ecosystems is accelerated eutrophication caused by nutrient over-enrichment, a problem often associated with agricultural production (USEPA 2002). Although many factors contribute to eutrophication, most attention has focused on the supply of carbon (C), nitrogen (N), and phosphorus (P). A comparison of N:P ratios among freshwater and estuary ecosystems indicated that freshwater ecosystems were

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